The effect of angle on change of direction biomechanics : comparison and inter-task relationships

Dos'Santos, T, Thomas, C and Jones, PA

http://dx.doi.org/10.1080/02640414.2021.1948258

Title	The effect of angle on change of direction biomechanics : comparison and inter-task relationships
Authors	Dos'Santos, T, Thomas, C and Jones, PA
Type	Article
URL	This version is available at: http://usir.salford.ac.uk/id/eprint/61263/
Published Date	2021

Journal of Sports Sciences

ISSN: (Print) (Online) Journal homepage: https://www.tandfonline.com/loi/rjsp20

The effect of angle on change of direction biomechanics: Comparison and inter-task relationships

Thomas Dos'Santos, Christopher Thomas & Paul A. Jones

To cite this article: Thomas Dos'Santos, Christopher Thomas & Paul A. Jones (2021): The effect of angle on change of direction biomechanics: Comparison and inter-task relationships, Journal of Sports Sciences, DOI: 10.1080/02640414.2021.1948258

To link to this article: https://doi.org/10.1080/02640414.2021.1948258

Published online: 18 Jul 2021.

JOURNAL OF SPORTS SCIENCES
https://doi.org/10.1080/02640414.2021.1948258

Routledge
Taylor & Francis Group

OPEN ACCESS Check for updates

The effect of angle on change of direction biomechanics: Comparison and inter-task relationships

Thomas Dos'Santos[a,b], Christopher Thomas[a] and Paul A. Jones[a]

[a]Human Performance Laboratory, Directorate of Sport, Exercise, and Physiotherapy, University of Salford, Greater Manchester, UK; [b]Department of Sport and Exercise Sciences, Musculoskeletal Science and Sports Medicine Research Centre, Manchester Metropolitan University, Manchester, UK

ABSTRACT

The aim of this was study to examine the inter-task relationships and compare change of direction (COD) biomechanics between different angles (45°, 90°, and 180°). Twenty-seven men performed three COD tasks, whereby lower-limb and trunk kinematics and kinetics were assessed via 3D motion and ground reaction force (GRF) analysis. Key mechanical differences ($p \leq 0.025$, $\eta^2 = 0.024$–0.940) in velocity profiles, GRF, sagittal joint angles and moments, multiplanar knee joint moments, and technical parameters existed between CODs. The primary findings were that as COD angle increased, velocity profiles decreased ($p < 0.001$, $d = 1.56$–8.96), ground contact times increased ($p < 0.001$, $d = 3.00$–5.04), vertical GRF decreased ($p < 0.001$, $d = 0.87$–3.48), and sagittal peak knee joint moments decreased ($p \leq 0.040$, $d = 0.62$–2.73). Notably, the greatest peak knee internal rotation (KIRMs) and abduction moments (KAMs) and angles were observed during the 90° COD ($p < 0.001$, $d = 0.88$–1.81), indicating that this may be the riskiest COD angle. Small to very large ($r = 0.260$–0.702) associations in KAMs and KIRMs were observed between tasks, indicating that evaluations at different angles are needed to develop an athlete's biomechanical injury risk profile. The results support the concept that COD biomechanics and potential surrogates of non-contact anterior cruciate ligament injury risk are "angle-dependent"; which have important implications for COD coaching, screening, and physical preparation.

ARTICLE HISTORY
Accepted 23 June 2021

KEYWORDS
Cutting; side-step; knee abduction moment; screening; anterior cruciate ligament

Introduction

Change of direction (COD) is defined as a "reorientation and change in the path of travel of the whole-body centre of mass (COM) towards a new intended direction" (David et al., 2018; Wyatt et al., 2019), and the ability to rapidly change direction is an important action associated with successful performance in multidirectional sports (Bloomfield et al., 2007; Karcher & Buchheit, 2014; Sweeting et al., 2017). For example, soccer players can perform ~600 cuts of 0–90° and ~100 turns of 90–180° during matches (Bloomfield et al., 2007), while directional changes of 45°, 90° and 180° are frequently performed in netball (Sweeting et al., 2017). Thus, the ability for athletes to be proficient at changing direction from shallow (≤45°), moderate (45–90°), and sharper (90–180°) angles is considered to be highly important for expressions of agility within sport, such as getting into space to receive a pass, pressing opponents, making interceptions, and gaining territorial advantage in multidirectional sport (Dos'Santos et al., 2018; Nimphius, 2017).

A COD typically involves an athlete adopting a lateral foot plant to change their base of support relative to their COM to redirect and accelerate towards the new intended direction (Clarke et al., 2018). The lateral foot plant is commonly described as the final foot contact (FFC) and plays a crucial role in facilitating effective COD (Andrews et al., 1977). Additionally, in order to reduce momentum prior to the FFC, athletes decelerate whereby high braking forces are produced over the penultimate foot contact (PFC) (second to last foot contact involved with COD) and potentially steps prior (Bourgeois et al., 2017; Dos'Santos et al., 2018; Dos'Santos, Thomas et al., 2019). Importantly, the biomechanical demands of COD are "angle-dependent" (Dos'Santos et al., 2018; Havens & Sigward, 2014, 2015b), whereby the deceleration and reacceleration requirements (performance variables), GRF, knee injury risk surrogates, trunk and lower limb kinematics and kinetics, and lower-limb muscle activity vary across CODs of different angles (Dos'Santos et al., 2018). For example, reductions in approach velocity are observed with sharper CODs (Hader et al., 2014, 2015; Havens & Sigward, 2014), while braking forces and impulse (Havens & Sigward, 2014; Schot et al., 1995; Sigward et al., 2015), and GCT (Dos'Santos et al., 2018; Havens & Sigward, 2014) increase with sharper CODs. Notably, joint and segmental differences during the deceleration and redirection phases of COD have been reported between different angles. For example, Havens and Sigward (Havens & Sigward, 2015b) reported the hip was integral for propulsion during 45° CODs, but primarily acted as a stabiliser during 90° CODs with a greater reliance on the knee for deceleration, highlighting the task-dependent nature of COD.

CODs, usually in response to visual stimuli, are also a key action associated with non-contact anterior cruciate ligament (ACL) injuries in multidirectional sports (Koga et al., 2010; Montgomery et al., 2018; Walden et al., 2015). This occurrence

CONTACT Thomas Dos'Santos t.dossantos@edu.salford.ac.uk Human Performance Laboratory, Directorate of Sport, Exercise, and Physiotherapy, University of Salford, 4.07 All Saints Building, Manchester Campus John Dalton Building, Manchester Campus, Greater Manchester, UK
Supplemental data for this article can be accessed online https://doi.org/10.1080/02640414.2021.1948258.

can be attributed to the potential to generate large multiplanar knee flexion, rotation and abduction moments (Besier et al., 2001; Dempsey et al., 2009; Dos'Santos, McBurnie et al., 2019), at extended knee postures, that can load and strain the ACL (Kiapour et al., 2016; Markolf et al., 1995; Shin et al., 2011). The potentially hazardous knee joint moments are amplified when biomechanical deficits (i.e., poor movement quality) are displayed, such as knee valgus, lateral trunk flexion, limited knee flexion, hip internal rotation, and greater vertical GRF (Dos'Santos, McBurnie et al., 2019; Fox, 2018; Weir et al., 2019). Greater knee valgus and extended knee postures have been observed with sharper CODs (Cortes et al., 2011; Dos'Santos et al., 2017). Additionally, greater external knee abduction moments (KAMs), and thus potential ACL loading (Kiapour et al., 2016; Markolf et al., 1995; Shin et al., 2011), have been observed with greater COD angles, such as 30° vs 60° (Besier et al., 2001), 45° vs 110° (Sigward et al., 2015), 45° vs 90° (Havens & Sigward, 2015a), and 45° vs 180° (Cortes et al., 2011); thus greater angled CODs may increase potential ACL loading.

To the best of our knowledge only one investigation (Schreurs et al., 2017) has compared KAMs between more than two COD angles (45°, 90°, 135°, and 180°) and reported greater KAMs in sharper COD tasks compared to 45° CODs, but a stabilisation in KAMs and lack of meaningful differences between 90°, 135°, 180° CODs were observed. Importantly, however, the aforementioned investigations have only examined and compared KAMs between COD tasks, and have not considered knee internal rotation moments (KIRM). This absence is important because ACL strain is amplified when a combination of high frontal and transverse knee moments at extended knee postures are generated, in comparison to uniplanar loading (Bates et al., 2015; Kiapour et al., 2016; Shin et al., 2011). Furthermore, previous research (Schreurs et al., 2017) only examined knee flexion angles, moments, KAMs, and vertical GRF between tasks, failing to examine hip, ankle, and trunk kinematics and kinetics which have been reported to play a pivotal role in terms of performance (Marshall et al., 2014; Sasaki et al., 2011; Welch et al., 2021) and knee joint loads (Dos'Santos, McBurnie et al., 2019; Fox, 2018; Weir et al., 2019).

Because ACL injuries can be a career-threatening injury with negative short- and long-term consequences (i.e., economic, health, psychological) (Cumps et al., 2008; Hewett, 2017; Lohmander et al., 2007), the ability to identify athletes' potentially "at-risk" (i.e., "higher-risk") of injury is a critical step in effective ACL injury risk reduction (Fox et al., 2017; Hewett, 2017). Movement screening via three-dimensional (3D) and GRF analysis is used to identify "higher-risk" athletes that display poor movement quality (i.e., knee valgus) and high multiplanar knee joint moments (surrogates of non-contact ACL injury risk) (Herrington et al., 2018). "High-risk" athletes can therefore be targeted with individualised training interventions to reduce potential injury risk. However, a problematic issue is that an athlete's "biomechanical injury risk profile" is task dependent, whereby an athlete displaying high-risk mechanics during one task, may not necessarily display high-risk mechanics during a different task, and vice versa (Chinnasee et al., 2018; Jones et al., 2014; Kristianslund & Krosshaug, 2013; Munro et al., 2017). This can therefore lead to different evaluations and interpretations regarding an athlete's potential injury risk and training recommendations. To our knowledge, only one study has examined the relationships between KAMs between different CODs angles, reporting a large correlation (r = 0.56) between 90° and 180° CODs in female soccer players (Jones et al., 2014). However, the shared variance was only 31% which suggests different evaluations regarding potential injury risk should be made and thus, assessing CODs of different angles might be required for screening and profiling potential ACL injury risk.

Currently, there is a paucity of research that has comprehensively examined the effects of angle on COD biomechanics, while considering PFC braking characteristics and KIRMs. Therefore, the aim of this study was three-fold: 1) to compare COD performance, knee injury risk surrogates, GRF, and trunk and lower-limb kinetics and kinematics between CODs of 45°, 90°, and 180°; 2) to examine the inter-task relationships in the aforementioned biomechanical variables between different COD angles; and 3) to assess agreements in "high" and "low" knee joint load classification for KAMs and KIRMs between COD angles. It was hypothesised that greater braking forces, longer ground contact times (GCT), lower velocity profiles, greater sagittal plane lower-limb flexion, greater pelvis rotation and initial foot progression angles, and multiplanar knee joint moments and knee abduction angles (KAA) would be displayed during sharper CODs compared to moderate and shallow, and that poor relationships would be demonstrated for COD biomechanical variables between COD angles. Exploratory analysis was performed to investigate potential differences and relationships for sagittal plane lower limb moments and lateral trunk flexion angle between COD tasks. It was hypothesised that athletes would not consistently display "high" or "low" knee joint load injury risk surrogates between tasks, thus injury risk profile would be task dependent. Further research is needed that comprehensively compares multi-joint COD biomechanics and multiplanar knee joint moments during shallow, moderate, and sharp CODs to improve our understanding regarding COD task execution and potential knee injury risk.

Methods and materials

Participants

Twenty-seven men (age: 22.9 ± 5.1 years, mass: 77.6 ± 12.5 kg, height: 1.78 ± 0.07 m) from multiple sports (soccer n = 19, rugby n = 7, field-hockey n = 1) participated in this study, with 25 participants stating right-limb dominance (preferred kicking limb). A minimum sample size of 27 was determined from an *a priori* power analysis using G*Power (Version 3.1, University of Dusseldorf, Germany) (Faul et al., 2009) to detect a moderate effect size (ES) for a paired t-test (0.60), at a power of 0.80, and type 1 error (0.05). A moderate effect size was considered as a practically relevant and the smallest effect size of interest for this study (Hopkins, 2004; Lakens, 2021). For inclusion in the study, all athletes had played their respective sport for a minimum of 5 years at a semi-professional level and regularly participated in one game and performed two structured skill-based training sessions per week. All athletes were free from injury and had never suffered a prior traumatic knee injury such as an ACL injury. At the time of testing, players were currently in-season and also performed two resistance training sessions a week as part of a strength mesocyle. Testing took place a minimum of 48 hours post-competitive fixture. The investigation was approved by the Institutional Ethics Review Board, and all participants were informed of the benefits and risks of the investigation prior to signing an institutionally approved consent document to participate in the study.

Experimental protocol

All participants performed a 5-minute warm-up consisting of jogging, self-selected dynamic stretching, and familiarisation trials of the COD tasks (4 trials performed submaximally at 75% of perceived maximal effort); similar to the warm up procedures utilised in previous studies (Dai et al., 2014; Vanrenterghem et al., 2012). The marker placement and 3D motion analysis procedures were based on previously published methodologies (Dos'Santos et al., 2020; Dos'Santos, McBurnie et al., 2019; Jones et al., 2016a); thus, a brief overview is provided here.

Participants performed six trials each of a 45° (COD45), 90° (COD90) and 180° (COD180) COD task as fast as possible in a sequential order. The 45° and 90° COD tasks consisted of a 5-m entry and 3-m exit, whereas the 180° COD consisted of a 5-m entry and exit (Supplementary material 1), and were performed on an indoor running track (Mondo, SportsFlex, 10 mm; Mondo America Inc., Mondo, Summit, NJ, USA). For all tasks, participants adopted a two-point stance 0.5 m behind the start line, to prevent early triggering of the timing gates, and sprinted as fast as possible in a straight line to the turning point before changing direction from their right limb and exiting towards the finish line. Each trial was interspersed with 2 minutes' rest. If the participant slid, turned prematurely, or missed the force platform(s), the trial was discarded and subsequently another trial was performed after 2 minutes' rest. Completion time was measured using sets of single beam Brower timing lights (Draper, UT, USA) that were set at approximate hip height for all participants (Yeadon et al., 1999).

Prior to the COD tasks, reflective markers (14 mm spheres) were placed on lower-limb and torso bony landmarks of each participant by the lead researcher (Dos'Santos et al., 2020; Jones et al., 2016a, 2017). Each participant wore a four-marker "cluster set" (four retroreflective markers attached to a lightweight rigid plastic shell) on the right and left thigh and shin which approximated the motion of these segments during the dynamic trials. All participants wore lycra shorts and standardised footwear (Balance W490, New Balance, Boston, MA, USA) to control for shoe–surface interface.

Data analysis

Marker and GRF data were collected over the PFC and FFC using ten Qualisys Oqus 7 (Gothenburg, Sweden) infrared cameras (240 Hz) operating through Qualisys Track Manager (QTM) software (Qualisys, version 2.16 (Build 3520), Gothenburg, Sweden) and GRFs were collected from two 600 mm × 900 mm AMTI (Advanced Mechanical Technology, Inc, Watertown, MA, USA) force platforms (Model number: 600900) embedded into the running track sampling at 1200 Hz. The kinematic model process was based on previous reported methodologies, whereby a static trial position was designated as the subject's neutral (anatomical zero) alignment, and subsequent kinematic and kinetic measures were related back to this position (Dos'Santos et al., 2020; Dos'Santos, McBurnie et al., 2019; Jones et al., 2016a). Using the pipeline function in Visual 3D software (C-motion, version 6.01.12, Germantown, USA), joint coordinate (marker) and force data were smoothed using a Butterworth low-pass digital filter with cut-off frequencies of 15 and 25 Hz, based on *a priori* residual analysis (Winter, 2009), visual inspection of motion data, and research recommendations (Roewer et al., 2014). Lower limb joint moments were calculated using an inverse dynamics approach (Winter, 1990) through Visual 3D software and were defined as external moments and normalised to body mass.

The trials were time normalised for each participant to 101 data points with each point representing 1% of the weight acceptance (WA) phase of the COD. Initial contact (IC) was defined as the instant after ground contact that the vertical GRF (VGRF) was higher than 20 N, and end of contact was defined as the point where the VGRF subsided past 20 N (Jones et al., 2016b; Kristianslund et al., 2014, 2012). The WA phase was defined as IC to the point of maximum knee flexion (Havens & Sigward, 2015a; Jones et al., 2015, 2016a). Velocities at key instances of the COD (PFC touch-down – approach), FFC touch-down, and FFC toe-off (exit) were determined using the horizontal COM velocity using the combined lower-limb and trunk model (Vanrenterghem et al., 2010) (Supplementary material 2).

Joint kinematics and GRF were also calculated using Visual 3D, with Supplementary material 2 providing the variables examined, definitions, and calculations. Briefly, the following kinetic and kinematics were examined during the FFC: GCT and velocity at FFC and exit velocity (performance variables); peak KAMs, peak KIRMs, and peak and IC knee abduction angles (knee injury risk surrogates); VGRF; hip, knee, ankle dorsiflexion moments and angles (sagittal plane joint moment and angles); lateral trunk flexion, pelvis rotation, initial foot progression angle (IFPA) (trunk, pelvis, and foot variables). Horizontal GRF was examined for the PFC only, while approach velocity was also examined and considered a performance variable. Five trials for each angle were used for the analysis for each participant based on visual inspection of motion files (Jones et al., 2016a) and the average of individual trial peaks for each variable were calculated (Dos'Santos et al., 2020).

Statistical analyses

All statistical analysis was performed in SPSS v25 (SPSS Inc., Chicago, IL, USA) and Microsoft Excel (version 2016, Microsoft Corp., Redmond, WA, USA). Normality was inspected for all variables using a Shapiro–Wilk test. COD biomechanical variables were compared across the three COD tasks using a repeated measures analysis of variance (RMANOVA), with Bonferroni post-hoc pairwise comparisons in cases of significant differences for parametric variables. Partial eta squared ESs were calculated for all RMANOVAs, with the values of 0.010–0.059, 0.060–0.149, and ≥ 0.150 considered as small, medium, and large, respectively, according to Cohen (Cohen, 1988). For non-parametric variables, a Friedman's test was used, and in cases of significant differences, individual Wilcoxon-sign ranked tests were used to explore differences. Cohen's *d* ESs were calculated for all pairwise comparisons between tasks, and interpreted as trivial (≤0.19), small (0.20–0.59), moderate (0.60–1.19), large (1.20–1.99), very large (2.00–3.99), and extremely large (≥4.00) (Hopkins, 2002).

Inter-task relationships for all dependant variables between tasks were examined using Pearson's (parametric data) and Spearman's (non-parametric data) correlations. Correlations were evaluated as follows: trivial (0.00–0.09), small (0.10–0.29), moderate (0.30–0.49), large (0.50–0.69), very large (0.70–0.89), nearly perfect (0.90–0.99), and perfect (1.00) (Hopkins, 2002). A correlation cut-off value of ≥ 0.40 was considered relevant (Welch et al., 2021).

Finally, similar to previous research (Chinnasee et al., 2018), percentage agreements in "high" and "low" knee joint load classification for peak KAMs and KIRMs were performed between tasks, with moments greater than mean+0.5 standard deviations considered "high" and moments lower than this threshold considered "low". Like-for-like identifications in "high" or "low" knee joint loads classifications between the three COD tasks were performed and subsequent percentage agreements were calculated. Percentage agreements were interpreted with the following scale (Cortes & Onate, 2013; Onate et al., 2010): excellent (>80%), moderate (51–79%), and poor (<50%) (Cortes & Onate, 2013; Onate et al., 2010). Statistical significance was defined $p \leq 0.05$ for all tests.

Results

Descriptive statistics and the results of the RMANOVA, Friedman's test, and pairwise comparisons in COD biomechanics between tasks are presented in Table 1. Inter-task relationships in COD biomechanics are presented in Table 2.

COD task comparisons and inter-task relationships

Performance variables

RMANOVA revealed significantly large effects of COD task on performance variables (Table 1). As COD angle increased, GCTs increased, and approach, FFC, and exit velocity reduced linearly between tasks (Table 1, Figure 1). Relevant, large to very large relationships were observed between all tasks for approach velocity. Moderate to large relationships for FFC velocity and exit velocity were observed between COD45 and COD90; and COD90 and COD180 (Table 2).

Knee injury risk surrogates

RMANOVA revealed significant, large effects of COD task on knee joint moments and peak and IC KAA (Table 1). Moderately to largely greater peak KAMs and KIRMs were demonstrated during the COD90 in comparison to COD45 and COD180 (Table 1, Figure 2). Conversely, non-significant and trivial differences in peak KAMs and KIRMs were observed between COD45 and COD180 (Table 1, Figure 2). Relevant, large to very large relationships were observed between all tasks for peak KAMs. No

Table 1. Task comparisons in COD biomechanics.

		COD45		COD90		COD180				COD45 vs COD90		COD45 vs COD180		COD90 vs COD180	
	Variable	Mean	SD	Mean	SD	Mean	SD	RMANOVA	η^2	*p*	*d*	*p*	*d*	*p*	*d*
Performance	GCT (s)	0.203	0.025	0.302	0.039	0.510	0.083	<0.001**	0.901	<0.001**	3.00	<0.001**	5.04	<0.001**	3.22
	Approach velocity (m/s)	5.22	0.25	4.51	0.32	4.00	0.33	<0.001**	0.940	<0.001**	−2.52	<0.001**	−4.18	<0.001**	−1.56
	Velocity at FFC (m/s)	5.06	0.30	3.43	0.26	2.68	0.29	<0.001**	0.969	<0.001**	−5.81	<0.001**	−8.15	<0.001**	−2.75
	Exit velocity (m/s)	5.27	0.42	3.29	0.17	2.20	0.24	<0.001**	0.977	<0.001**	−6.17	<0.001**	−8.96	<0.001**	−5.21
Knee injury risk surrogates	pk KAM (Nm/kg)	0.83	0.40	1.19	0.42	0.85	0.26	<0.001**	0.440	<0.001**	0.88	1.000	0.05	<0.001**	−0.98
	pk KIRM (Nm/kg)	−0.50	0.32	−1.00	0.37	−0.48	0.16	<0.001**	0.574	<0.001**	−1.44	1.000	0.09	<0.001**	1.81
	KAA – pk (°)	−9.8	6.0	−12.5	6.9	−11.7	5.6	0.003*	0.196	0.011*	−0.41	0.105	−0.31	0.583	0.13
	KAA – IC (°)	2.5	4.7	3.4	3.7	0.6	3.7	0.010*	0.186	0.538	0.22	0.238	−0.44	0.003*	−0.76
GRF	pk VGRF (BW)	*3.75*	*1.02*	2.88	0.97	1.16	0.23	*<0.001***		<0.001**	−0.87	<0.001**	−3.48	<0.001**	−2.43
	PFC pk HGRF (BW)	−0.68	0.30	−1.60	0.53	−1.54	0.19	<0.001**	0.024	<0.001**	−2.13	<0.001**	−3.44	0.866	0.15
Sagittal moments	pk HFM (Nm/kg)	4.09	1.24	3.24	0.81	2.15	0.73	<0.001**	0.588	0.002*	0.82	<0.001**	1.91	<0.001**	1.41
	pk KFM (Nm/kg)	3.93	0.62	3.44	0.46	2.53	0.39	<0.001**	0.726	0.003*	0.92	<0.001**	2.73	<0.001**	2.13
	pk ADFM (Nm/kg)	1.97	0.43	1.71	0.36	1.68	0.51	0.007*	0.198	0.002*	0.66	0.040*	0.62	1.000	0.07
Sagittal joint angles	HFA – pk (°)	54.0	8.0	51.1	7.4	60.0	7.9	<0.001**	0.348	0.213	−0.38	0.017	0.75	<0.001**	1.16
	KFA – pk (°)	55.8	5.5	64.2	5.7	67.3	7.2	<0.001**	0.689	<0.001**	1.49	<0.001**	1.81	<0.001**	0.49
	ADFA – pk (°)	77.9	5.2	77.3	6.0	82.4	11.5	0.025*	0.154	1.000	−0.10	0.181	0.51	0.017	0.56
	HFA – IC (°)	53.0	8.1	47.4	6.6	37.1	7.0	<0.001**	0.681	0.001**	−0.76	<0.001**	−2.10	<0.001**	−1.50
	KFA – IC (°)	27.4	6.4	23.5	5.0	20.6	3.8	<0.001**	0.415	0.004*	−0.67	<0.001**	−1.28	0.015	−0.65
	ADFA – IC (°)	57.5	5.9	51.6	7.1	48.5	6.4	<0.001**	0.475	<0.001**	−0.91	<0.001**	−1.46	0.099	−0.45
Trunk, pelvis, foot	Lateral trunk flexion – IC (°)	−20.9	7.6	−18.0	9.0	7.4	9.3	<0.001**	0.859	0.131	0.35	<0.001**	3.33	<0.001**	2.77
	Pelvis rotation (°)	4.6	6.7	30.7	11.2	82.1	18.8	<0.001**	0.937	<0.001**	2.85	<0.001**	5.50	<0.001**	3.33
	IFPA (°)	−1.0	6.3	13.6	10.7	54.2	19.3	<0.001**	0.872	<0.001**	1.66	<0.001**	3.84	<0.001**	2.60
Trivial ES	Small ES			Moderate/Medium ES				Large ES		Very Large ES				Extremely large ES	

SD: Standard deviation; BW: Body weight; COD45: Change of direction 45°; COD90: Change of direction 90°; COD180: Change of direction 180°; RMANOVA; Repeated measures analysis of variance; GCT: Ground contact time; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; KAA: Knee abduction angle; HFM: Hip flexion moment; ADFM: Ankle dorsi-flexion moment; IFPA: Initial foot progression angle; HFA: Hip flexion angle; KFA: Knee flexion angle; ADFA: Ankle dorsi-flexion angle; HRA: Hip rotation angle; IC: Initial contact; FFC: Final foot contact; PFC: Penultimate foot contact; VGRF: Vertical ground reaction force; HGRF: Horizontal ground reaction force; IFPA: Initial foot progression angle; pk: peak; *: $p \leq 0.05$; **: $p \leq 0.001$. Note italic denotes non-parametric equivalent was performed.

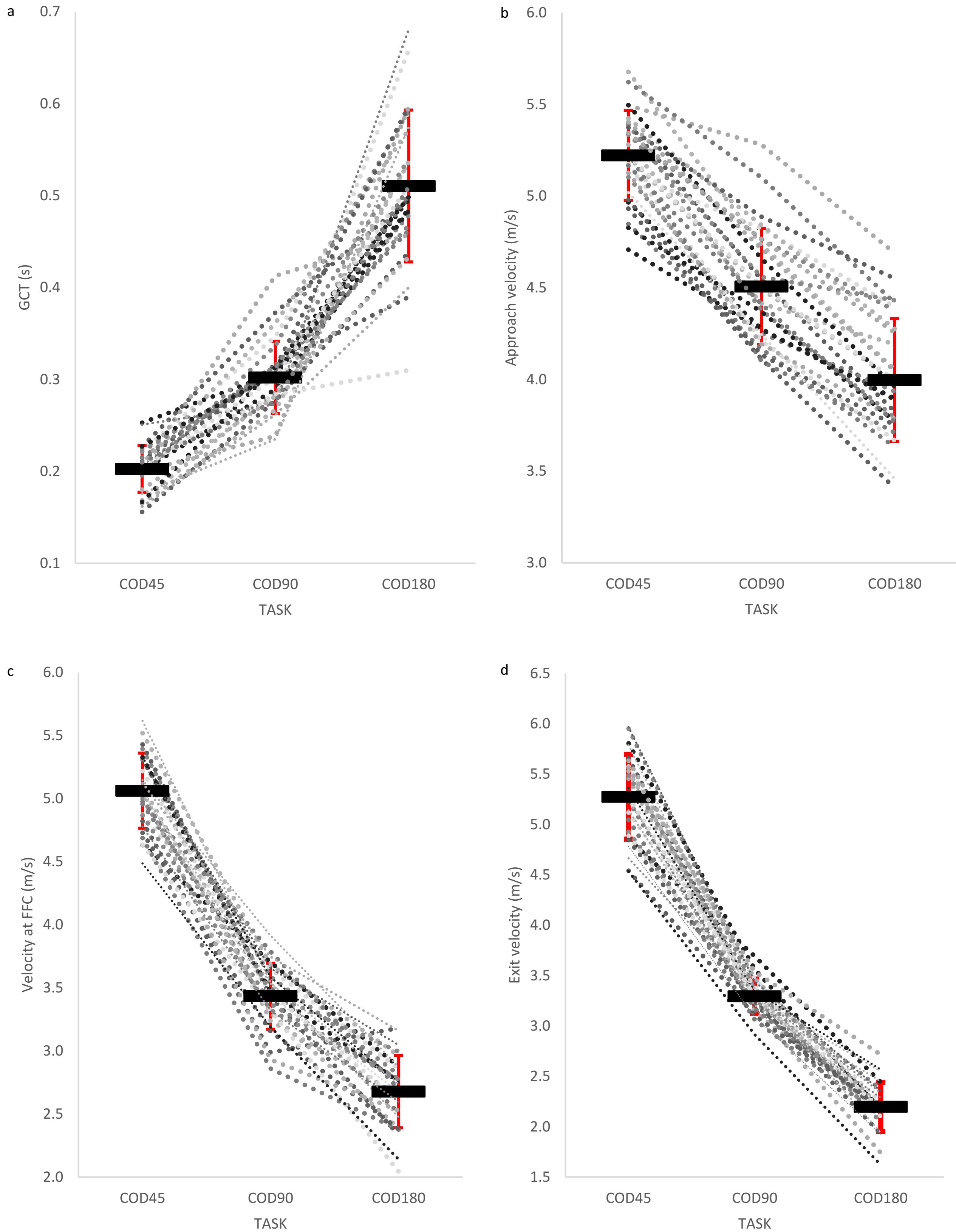

Figure 1. Task comparison in COD performance variables with individual plots (black rectangle denotes mean with SD error bars in red). (a) GCT; (b) Approach velocity; (c) Velocity at FFC; (d) Exit velocity.

Table 2. Inter-task correlations in COD biomechanics.

	Variable	COD45 vs COD90 r or ρ	COD45 vs COD90 r^2 (%)	COD45 vs COD180 r or ρ	COD45 vs COD180 r^2 (%)	COD90 vs COD180 r or ρ	COD90 vs COD180 r^2 (%)
	GCT	0.333	11.1	0.238	5.7	−0.073	0.5
Performance	Approach velocity	0.725	52.6	0.589	34.7	0.873	76.2
	Velocity at FFC	0.393	15.4	0.330	10.9	0.438	19.2
	Exit velocity	0.444	19.7	0.303	9.2	0.540	29.2
Knee injury risk variables	pk KAM	0.641	41.1	0.528	27.9	0.702	49.3
	pk KIRM	0.264	7.0	0.260	6.8	0.342	11.7
	KAA – pk	0.787	61.9	0.732	53.6	0.891	79.4
	KAA – IC	0.676	45.7	0.205	4.2	0.457	20.9
GRF	pk VGRF	0.752	56.6	−0.225	5.1	0.289	8.4
	PFC pk HGRF	0.368	13.5	−0.036	0.1	−0.147	2.2
Sagittal joint moments	pk HFM	0.460	21.2	0.008	0.0	0.307	9.4
	pk KFM	0.160	2.6	0.003	0.0	0.566	32.0
	pk ADFM	0.603	36.4	0.266	7.1	0.524	27.5
Sagittal joint angles	HFA – pk	0.463	21.4	0.158	2.5	0.405	16.4
	KFA – pk	0.613	37.6	0.520	27.0	0.595	35.4
	ADFA – pk	0.637	40.6	0.102	1.0	0.640	41.0
	HFA – IC	0.533	28.4	0.067	0.4	0.678	46.0
	KFA – IC	0.533	28.4	0.212	4.5	0.403	16.2
	ADFA – IC	0.662	43.8	0.156	2.4	0.455	20.7
Trunk, pelvis, foot	Lateral trunk flexion – IC	0.634	40.2	0.167	2.8	0.554	30.7
	Pelvis rotation	0.370	13.7	0.154	2.4	0.697	48.6
	IFPA	0.284	8.1	−0.012	0.0	0.662	43.8
Moderate	Large					Very Large	

Key: BW: Body weight; COD45: Change of direction 45°; COD90: Change of direction 90°; COD180: Change of direction 180°; GCT: Ground contact time; KAM: Knee abduction moment; KIRM: Knee internal rotation moment; KFM: Knee flexion moment; KAA: Knee abduction angle; HFM: Hip flexion moment; ADFM: Ankle dorsi-flexion moment; IFPA: Initial foot progression angle; HFA: Hip flexion angle; KFA: Knee flexion angle; ADFA: Ankle dorsi-flexion angle; HRA: Hip rotation angle; IC: Initial contact; FFC: Final foot contact; PFC: Penultimate foot contact; VGRF: Vertical ground reaction force; HGRF: Horizontal ground reaction force; IFPA: Initial foot progression angle; pk: peak.

relevant relationships were observed for peak KIRMs between tasks (Table 2).

Like-for-like agreements in "high" and "low" KAM and KIRMs classifications between COD tasks are presented in Table 3. Percentage agreements for "high/low" like-for-like identifications for KAMs between COD tasks were moderate to excellent (74–85%, Figure 3, Table 3). Percentage agreements between "high/low" like-for-like identifications for KIRMs between COD tasks were moderate (63–67%, Figure 4, Table 3),

Greater peak KAAs were observed only for COD90 compared to COD45, while IC KAAs were moderately greater for COD180 compared to COD90 only (Table 1). Relevant, very large relationships were observed between all tasks for peak KAA, while relevant, moderate to large relationships for IC KAA were revealed between COD45 and COD90, and COD90 and COD180 (Table 2).

GRF variables

Significant effects of COD task on GRF variables were observed (Table 1). VGRF moderately to very largely decreased as COD task angle increased (Table 1). Conversely, PFC HGRF was very largely lower during COD45 in comparison to COD90 and COD180, while trivial differences were observed between COD90 and COD180 (Table 1). Relevant, very large relationships were observed only for VGRF between COD45 and COD90 (Table 2).

Sagittal plane joint moments

RMANOVA revealed significant, large effects of COD task on sagittal plane joint moments (Table 1). Moderate to very largely greater peak hip (HFM), knee (KFM), and ankle dorsi-flexion moments (ADFMs) were demonstrated during COD45 in comparison to COD90 and COD180 (Table 1). Although peak HFMs were largely greater for COD90 compared the COD180, trivial differences in peak ADFMs were observed. Relevant, large relationships were observed for ADFMs between COD45 and COD90, and COD90 and COD180, while relevant, moderate associations for HFMs was observed between COD45 and COD90 (Table 2). A relevant, large relationship was revealed only between COD90 and COD180 for KFM (Table 2).

Sagittal plane joint angles

RMANOVA revealed significantly large effects of COD task for sagittal plane joint angles (Table 1). Small to largely greater peak hip (HFA) and knee flexion angles (KFA) were displayed during COD180 compared to the COD90 and COD45 (Table 1). The greatest peak ankle dorsi-flexion angles (ADFA) were demonstrated during the COD180, but this was greater than COD90 only (Table 1). Moderately to very largely greater initial HFA, KFA, and ADFA postures were observed during COD45 in comparison to the other COD tasks (Table 1). Relevant, large relationships were observed between all tasks for peak KFA, while relevant, moderate to large relationships were revealed only between COD45 and COD90, and COD90 and COD180 for peak and IC HFA, peak and IC ADFA, and KFA at IC (Table 2).

Trunk, pelvis, and foot variables

RMANOVA revealed significant, large effects of COD task on trunk, pelvis, and foot variables (Table 1, Figure 5). Largely to very largely greater pelvis rotation and IFPAs were demonstrated as COD angle increased across tasks, while lateral trunk flexion angles were lower during COD180 compared to COD90 and COD45 (Table 1). Relevant, large relationships were observed between COD45 and COD90, and COD90 and

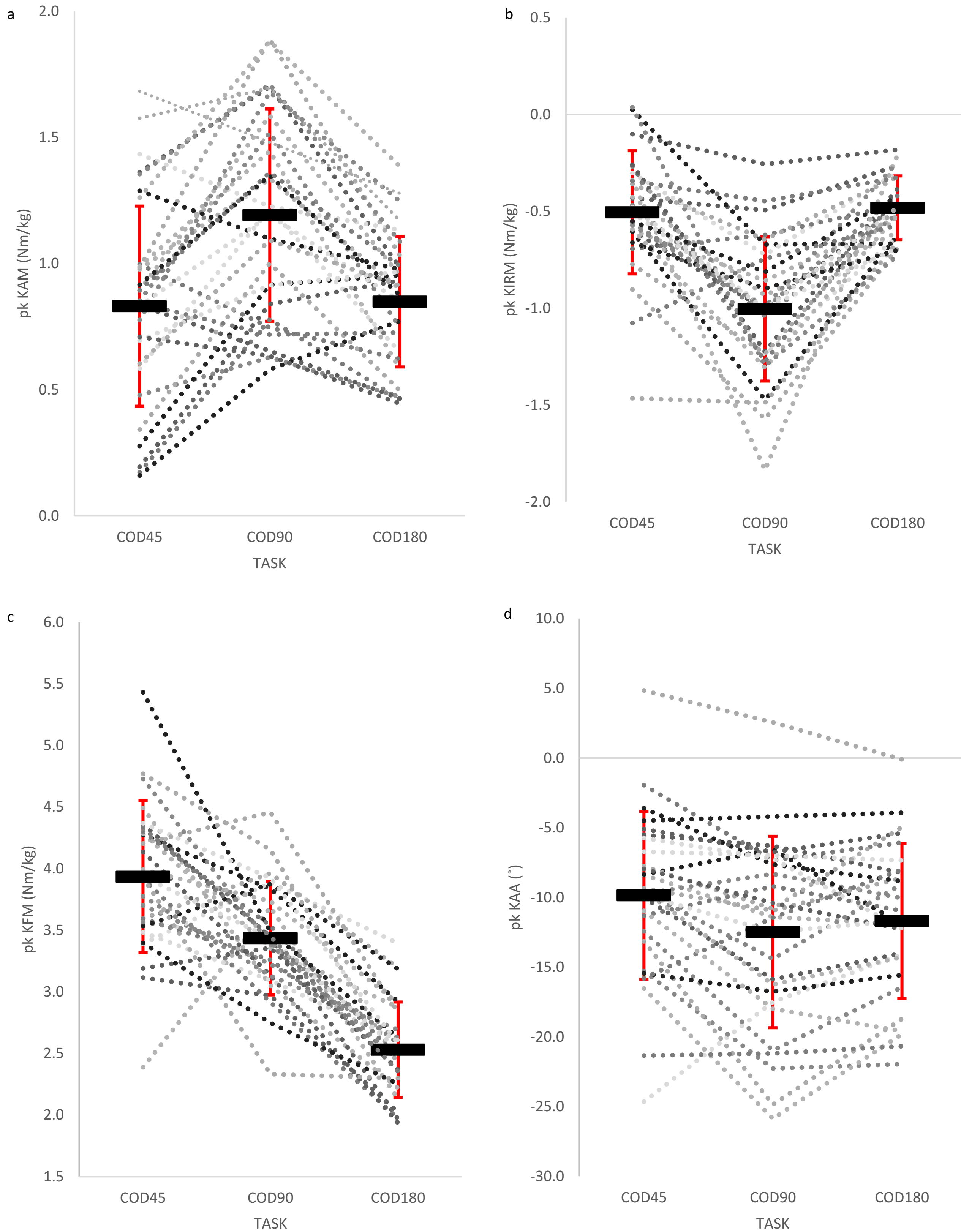

Figure 2. Task comparison in COD injury risk variables with individual plots (black rectangle denotes mean with SD error bars in red). (a) pk KAM; (b) pk KIRM: (c) pk KFM; (d) pk KAA.

Table 3. Like-for-like identifications in high and low knee joint load classifications for KAMS and KIRMs between COD tasks.

Like-for-like identifications in high and low KAM classifications	Number of subjects	Like-for-like identifications in high and low KAM classifications	Number of subjects	Like-for-like identifications in high and low KAM classifications	Number of subjects
High COD90-High COD45	4	High COD180-High COD45	5	High COD180-High COD90	6
Low COD90-Low COD45	16	Low COD180-Low COD45	18	Low COD180-Low COD90	16
High COD90-LowCOD45	5	High COD180-LowCOD45	3	High COD180-LowCOD90	2
High COD45-Low COD90	2	High COD45-Low COD180	1	High COD90-Low COD180	3
Number of subjects accurately identified as "high" or "low" between tasks	20/27 (74%) Moderate agreement	Number of subjects accurately identified as "high" or "low" between tasks	23/27 (85%) Excellent agreement	Number of subjects accurately identified as "high" or "low" between tasks	22/27 (82%) Excellent agreement
Like-for-like identifications in high and low KIRM classifications	**Number of subjects**	**Like-for-like identifications in high and low KIRM classifications**	**Number of subjects**	**Like-for-like identifications in high and low KIRM classifications**	**Number of subjects**
High COD90-High COD45	3	High COD180-High COD45	3	High COD180-High COD90	5
Low COD90-Low COD45	15	Low COD180-Low COD45	15	Low COD180-Low COD90	12
High COD90-LowCOD45	7	High COD180-LowCOD45	7	High COD180-LowCOD90	5
High COD45-Low COD90	2	High COD45-Low COD180	2	High COD90-Low COD180	5
Number of subjects accurately identified as "high" or "low" between tasks	18/27 (67%) Moderate agreement	Number of subjects accurately identified as "high" or "low" between tasks	18/27 (67%) Moderate agreement	Number of subjects accurately identified as "high" or "low" between tasks	17/27 (63%) Moderate agreement

Key: COD: Change of direction; KAM: Knee abduction moment; KIRM: Knee internal rotation moment.

COD180 for lateral trunk flexion angle (Table 2). Relevant, large relationships were observed for pelvis rotation and IFPA between COD90 and COD180 only (Table 2).

Discussion

The aim of this study was to examine the inter-task relationships and compare COD biomechanics between different angles (45°, 90°, and 180°); with a specific interest in ACL injury risk biomechanical surrogates. The primary findings were that key mechanical differences in velocity profiles, GRF, sagittal plane joint angles and moments, multiplanar knee joint moments, and trunk, pelvis, and foot parameters existed between COD tasks (Table 1, Figures 1–2 and Figure 5). As COD angle increased, performance variables declined with reductions in velocity profiles and longer GCTs (Table 1, Figure 1), supporting the study hypotheses. Additionally, VGRF and sagittal plane peak knee joint moments reduced with sharper CODs (Table 1), in contrast to the study hypotheses. Notably, refuting the study hypotheses, the greatest KAMs, KIRMs, and peak KAAs were observed during COD90, indicating that this may be the riskiest COD angle (Table 1, Figure 2). Percentage agreements in like-for-like identifications of high or low KAMs and KIRMs between COD angles were considered moderate to excellent (63–85%, Table 2, Figures 3 and Figure 4), indicating athletes generally display high moments across tasks. However, disagreements of ~20% and ~35% in "high/low" knee joint load classification between COD angles were observed (Tables 2–3, Figures 3 and Figure 4), respectively; thus, some caution is advised inferring potential injury risk between tasks.

Approach velocity, FFC velocity, and exit velocity declined with sharper CODs, while GCTs increased with sharper CODs (Table 1, Figure 1). These findings support the "angle-velocity trade-off" concept (Dos'Santos et al., 2018) and previous studies (Hader et al., 2015; Havens & Sigward, 2014; Schreurs et al., 2017), whereby as COD angle increases, approach velocity and velocity during COD declines, while GCTs increase in order to perform the intended COD and deflect the COM (Daniels et al., 2021; Dos'Santos et al., 2018; Havens & Sigward, 2014). Mechanically, shallow CODs have a reduced redirection and limited deceleration requirements, whereby minimising velocity decline is advantageous (Dos'Santos et al., 2018; Hader et al., 2015); highlighting the greater observed velocities and shorter GCTs for the shallow COD in the present study (Table 1, Figure 1).

Sharper side-steps may predispose athletes to greater non-contact ACL injury risk, due to the greater external KAMs and potential ACL loading observed compared to shallower CODs (Besier et al., 2001; Dos'Santos et al., 2018; Schreurs et al., 2017). The results of this study support this concept, with greater KAMs and peak KAAs displayed during COD90 compared to COD45 (Table 1, Figure 2) despite greater approach velocities during the COD45. Additionally, a novel aspect of this study was that KIRMs were investigated which, when combined with external KAMs, can produce greater ACL loading compared to uniplanar (Bates et al., 2015; Kiapour et al., 2016; Shin et al., 2011). Similar to KAM results, KIRMs were also greater during COD90 compared to COD45 (Table 1, Figure 2). Despite similar lateral trunk flexion angles observed between COD45 and COD90 (Table 1), the greater knee joint loads displayed during COD90 could be attributed to the greater peak KAAs, greater IFPAs, and pelvis rotation which are associated with greater KAMs (Dos'Santos, McBurnie et al., 2019; Fox, 2018), and leads to greater frontal and transverse plane deceleration and redirection requirements. Therefore, practitioners should acknowledge the postural and mechanical differences in COD when progressing and regressing side-stepping angle, and ensure they facilitate appropriate techniques according to the demands of the COD task.

In contrast to previous research (Jones et al., 2014; Schreurs et al., 2017), COD90 produced moderately greater KAMs compared to COD180 (Table 1, Figure 2). Jones et al. (Jones et al., 2014) observed no significant differences in KAMs between COD90 and COD180 in female soccer players, while Schreurs et al. (Schreurs et al., 2017) reported a stabilisation in KAMs between 90°, 135°, and 180°, but slightly greater KAMs for COD180. It is unclear why contrasting findings were observed

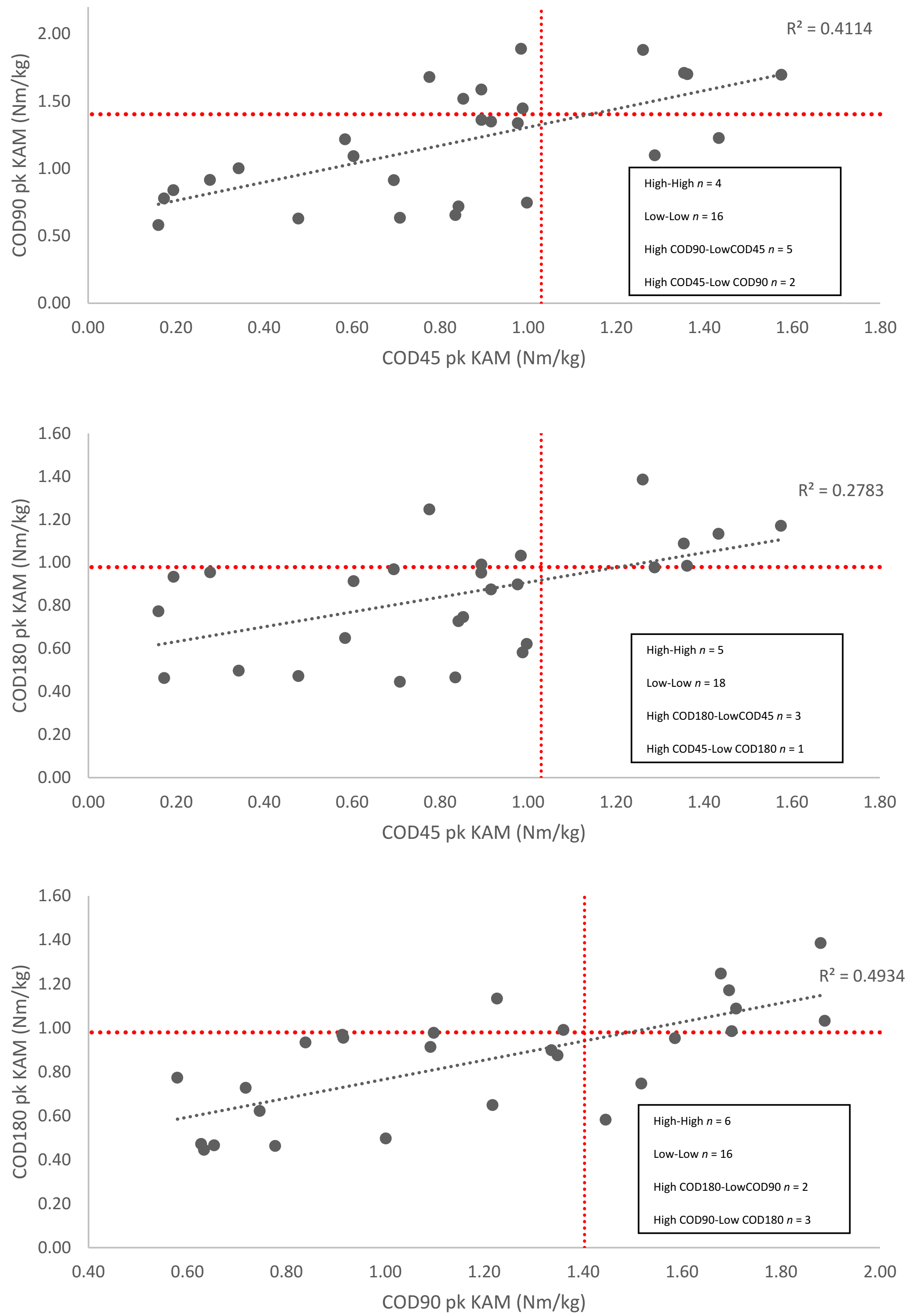

Figure 3. KAM inter-task correlations with high-/low thresholds (Red line denotes high threshold).

to Schreurs et al. (Schreurs et al., 2017), but the different results to Jones et al. (Jones et al., 2014) could be attributed to differences in task instruction and population sex. Jones et al. (Jones et al., 2014) instructed their population to complete a pivot technique, whereas in this study participants performed a COD strategy as fast as possible. However, the combination of the greater approach velocity, smaller hip and knee flexion angles and range of motion, and greater VGRF may have also contributed to greater knee joint loads (Fox, 2018; McBurnie et al., 2019; Weir et al., 2019) observed in the COD90 condition (Table 1).

During COD180, greater preliminary deceleration occurs and athletes tend to display a dual-support braking strategy whereby the PFC remains in contact with the ground during the turn (Dos'Santos, Thomas et al., 2019). This theoretically may help unload the FFC by more evenly distributing the loads

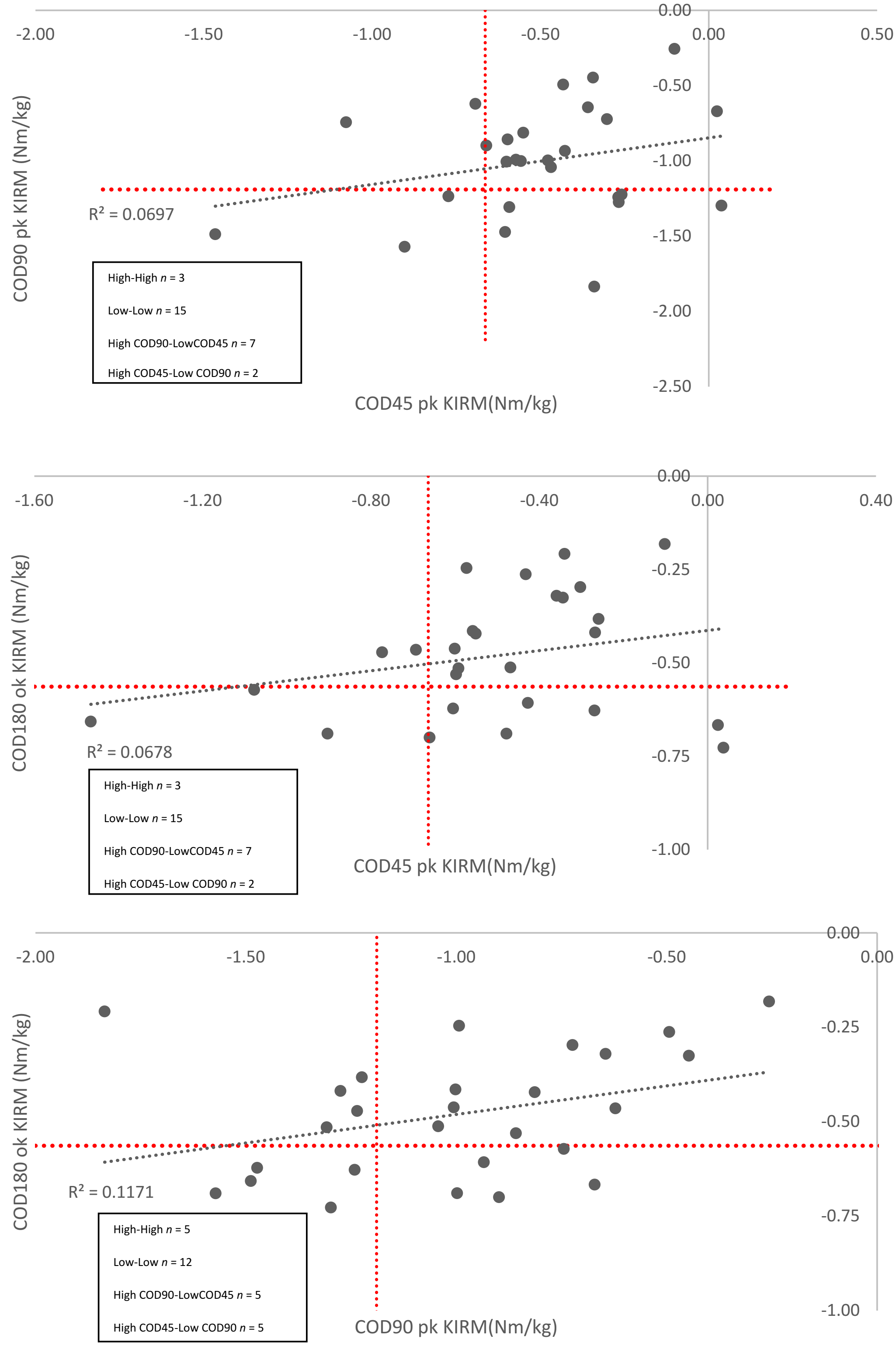

Figure 4. KIRM inter-task correlations with high-/low thresholds (Red line denote high threshold).

across two-foot contacts, in contrast to COD90 (Dos'Santos, Thomas et al., 2019). Additionally, a moderate relationship was observed between approach velocity and peak KAMs for COD90, whereas a small and irrelevant relationship between approach velocity and COD180 was present (Supplementary material 3) which may partially account for the greater KAMs during COD90. Especially given that approach velocity in this study is measured at touchdown of PFC and earlier foot contacts (e.g., antepenultimate) may well have reduced horizontal COM velocity by this point leading to lower knee joint loads at FFC during COD180 (Dos' Santos et al., 2021). Therefore, because of the greater peak KAMs, KIRMs, and KAAs, COD90 appears to be the "highest-risk" COD; thus, practitioners should ensure that athletes have the physical capacity (rapid force

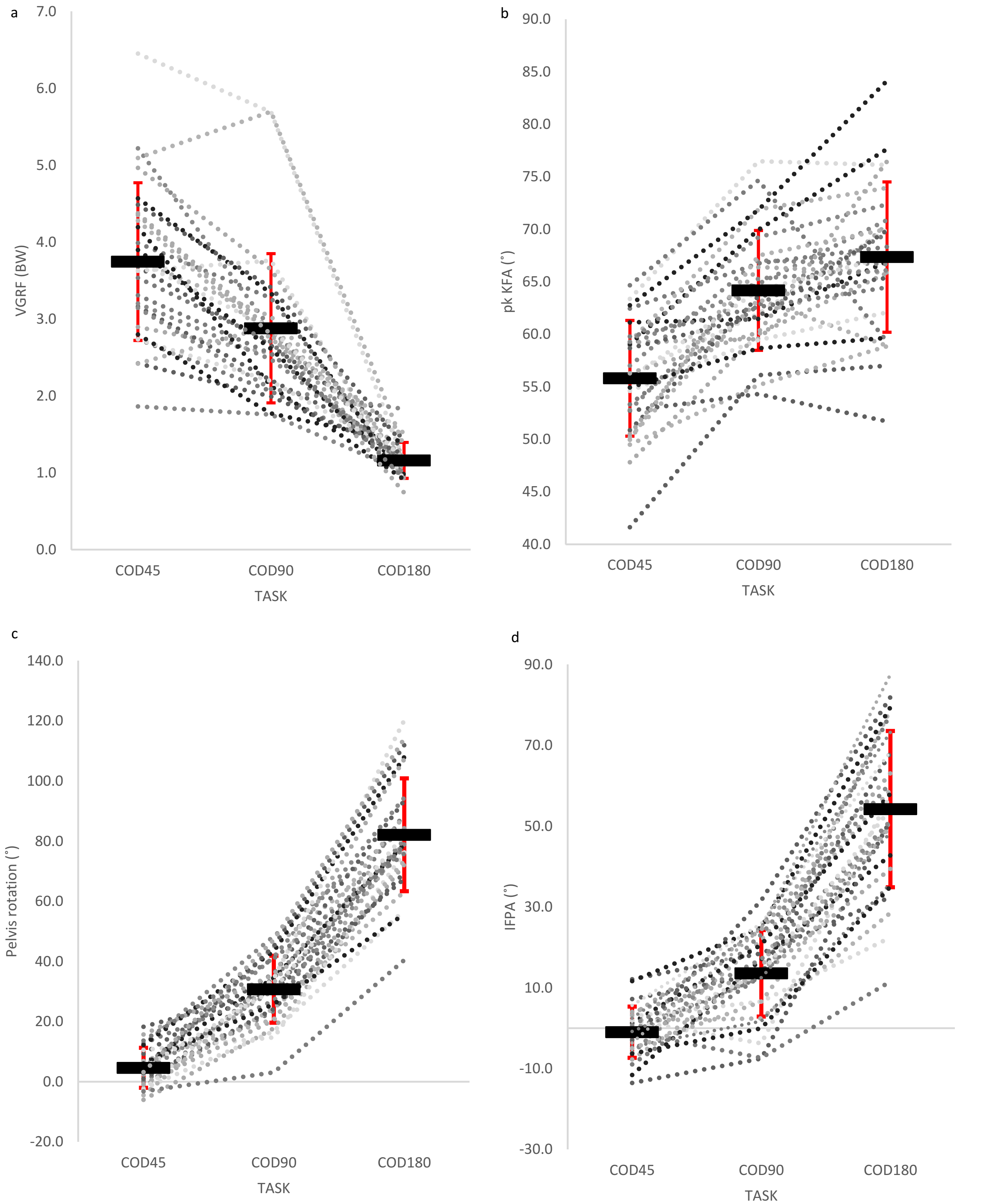

Figure 5. Task comparison in COD postural variables and VGRF with individual plots (black rectangle denotes mean with SD error bars in red). (a) VGRF; (b) pk KFA; (c) Pelvis rotation; (d) IFPA.

production, neuromuscular control, and muscle activation) to tolerate the greater knee joint loads associated with sharper side-steps (Dos'Santos et al., 2018; Jones et al., 2017; Lloyd & Buchanan, 2001; Maniar et al., 2018; Weinhandl et al., 2014). Consequently, practitioners should understand the implications of COD angle on knee joint loads when coaching COD, and should therefore progress intensity accordingly, particularly when working with novice or previously injured athletes rehabilitating from injury (Dos'Santos et al., 2018).

A problematic issue in movement screening is the task-dependent nature of ACL injury risk surrogates (Jones et al., 2014; Kristianslund & Krosshaug, 2013; Munro et al., 2017). Very large relationships were observed in peak KAAs between tasks (Table 2), similar to those observed in previous research (Jones et al., 2014) (r = 0.86, r^2 = 0.75) who, to our knowledge, is the only other investigation to examine the inter-task relationships of biomechanical surrogates of injury risk between two COD tasks. Additionally, large to very large relationships were observed in peak KAMs between COD angles (Table 2), similar to previous research (Jones et al., 2014), while moderate to excellent percentage agreements (74–85%) in like-for-like identifications in "high/low" KAMs were observed between COD tasks (Tables 2 and 3, Figure 3). Thus, athletes generally tend to display high or low KAMs consistently between tasks. Conversely, trivial to moderate relationships were observed for KIRMs between tasks (Tables 2 and 3), with slightly lower, but moderate percentage agreements (~65%) in like-for-like identifications in "high/ low" KIRMs observed between COD tasks (Table 2, Figure 4).

Despite ~80% and ~65% of athletes displaying agreements in "high" or "low" classification for KAMs and KIRMs, respectively, between tasks, disagreements in athletes classed as "high" or "low" KAMs and KIRMs between different COD angles were ~20% and ~35%, respectively. Thus, in some cases, an athlete displaying a "high/low" knee joint load during a specific COD angle, may not necessarily display a "high/low" knee joint load during a different angle, and vice versa (Tables 2 and 3, Figures 3 and Figure 4). Concerningly, this may lead to different evaluations regarding an athlete's biomechanical injury risk profile and, depending on the COD angle evaluated, different training recommendations could be prescribed. Collectively, these findings highlight the "angle-dependent" nature of injury risk profiling when using knee joint moments, thus caution is advised inferring potential injury risk between tasks: particularly KIRMs. It is therefore recommended that practitioners evaluate athletes' COD biomechanics across shallow, moderate, and sharp angles to ensure there are no misinterpretations regarding injury risk profiles.

Supporting the findings of previous research (Havens & Sigward, 2014), COD45 PFC braking forces were substantially lower compared to COD90 and COD180 (Table 1), indicating the minimal braking role the PFC has during shallow CODs. Conversely, COD90 and COD180 require greater preliminary deceleration to reduce momentum prior to the FFC to facilitate effective COD (Dos'Santos et al., 2018), as substantiated by the greater PFC braking forces and lower PFC and FFC velocities observed (Table 1). Furthermore, sharper CODs require longer GCTs to produce greater braking and propulsive impulse to overcome inertia which, in turn, facilitates effective net deceleration and net acceleration into the intended direction of travel (Dos'Santos et al., 2018; Havens & Sigward, 2014). Consequently, these findings substantiate the "angle-velocity trade-off" concept (Dos'Santos et al., 2018) and indicate that velocity profiles and GRF properties during COD are "angle-dependent". Thus, practitioners should be aware of the role of the PFC during shallow, moderate and sharper CODs, and consider coaching greater PFC braking strategies during the moderate and sharper CODs to facilitate effective deceleration prior to COD (Dos'Santos et al., 2018; Dos'Santos, Thomas et al., 2019), while encouraging velocity maintenance during shallow CODs (Dos'Santos et al., 2018; Dos'Santos, Thomas et al., 2019; Hader et al., 2015).

Key mechanical differences in sagittal plane joint moments and angles, and trunk, pelvis, and foot variables were observed between COD45 and COD180, including substantially lower sagittal plane moments, greater knee flexion angles, and greater IFPA and pelvis rotation for COD180 (Table 1, Figure 5). These results substantiate the findings of previous research that have reported greater pelvis rotation (Havens & Sigward, 2015b; Sigward et al., 2015) and lower sagittal plane moments (Havens & Sigward, 2015b; Schreurs et al., 2017) during sharper CODs. Generally, there were a limited number of relevant and meaningful correlations in COD biomechanics between the aforementioned angles (Table 2). This is unsurprising due to the substantially greater pre-rotation and redirection requirements to COD180, the requirement to reduce velocity the COM close to zero, and COD180 typically involves a dual-foot contact turning strategy in contrast to the lateral side-step cutting action displayed during 45° side-step cutting (Dos'Santos, Thomas et al., 2019; Jones et al., 2017). Despite the abovementioned mechanical differences, trivial differences in peak KAMs and KIRMs were observed between COD45 and COD180. Consequently, these findings highlight the task- and angle-dependent nature of COD.

It should be noted that the results of the present study are specific to the population and laboratory and methodological procedures adopted in this investigation. A sequential testing order was adopted which may have induced fatigue for the latter tasks; however, 2 minutes' rest was provided between each trial. Due to laboratory configuration, testing was only conducted on the subjects' right limb which was consistent between tasks. Finally, kinetic and kinematic data were calculated in relation to an anatomical standing posture, which may increase the susceptibility "cross-talk" between anatomical planes, particularly at the knee joint (Baudet et al., 2014). Therefore, it could be speculated that the inter-task correlations for KAMs and KIRMs could be slightly inflated and influenced by cross-talk, though further research is necessary to support this contention.

The present study did not control for approach velocity; however, this was done to increase the ecological validity to COD actions that are performed maximally in sport, and similar to the protocol of Schreurs et al. (Schreurs et al., 2017). Unfortunately, an ANCOVA could not be performed to compare knee joint loads (dependent variable) across angles with approach velocity as a covariate, because the data violated the assumptions to permit analysis (i.e., linear relationship and homogeneity of regressions – Supplementary material 3) (Vincent & Weir, 2012). To establish whether approach velocity was a confounding factor in terms of knee joint loads, we examined the relationship between approach velocity and knee joint loads for each COD angle (Supplementary material 3). Approach velocity had a large relationship with COD45 KAMs and a moderate relationship with COD90 KAMs, explaining ~32% and ~16% shared variance, respectively (Supplementary material 3). Thus, approach velocity appears to have a partial influence on KAMs during side-step cutting tasks, in line with previous research (Dos'Santos et al., 2021; McBurnie et al., 2019; Vanrenterghem et al., 2012). Conversely, a small relationship was observed between approach velocity and COD180 KAMs, and trivial to small relationships were observed between approach velocity and peak KIRMs across all COD angles (Supplementary material 3) accounting for ≤ 6% common variance. Therefore, approach velocity appears to have a negligible effect on peak KAMs for 180° turning tasks and KIRMs irrespective of angle in this population and specific conditions, in contrast to previous work (Dos'Santos et al., 2021; McBurnie et al., 2019). Thus, the greater KIRMs observed for COD90 compared to COD45 and COD180 (Table 1) appear to be attributable to mechanical differences.

Conclusions

COD angle has a significant and meaningful effect on COD biomechanics, with the results of the study substantiating the concept that the biomechanical demands of COD are "angle-dependent"; which have important implications with respect to COD coaching, screening, and physical preparation. The primary findings were that key mechanical differences in velocity profiles, GRF, sagittal plane joint angles and moments, KAMs and KIRMs, and postural parameters existed between COD45, COD90, and COD180. As COD angle increased, performance variables declined with reductions in velocity profiles and longer GCTs, supporting the "angle-velocity trade-off" concept. The greatest peak KAMs, KIRMs, and KAAs were observed during the COD90, indicating that this may be the riskiest COD angle. Generally, athletes tended to display "high" or "low" KAMs consistently between tasks, with moderate to excellent percentage agreements in "high/low" KAMs classification observed. Conversely, the relationships and classifications in KIRMs between tasks were lower with weaker correlations and lower percentage agreements in "high/low" KIRMs classifications observed. Disagreements of ~20% and ~35% in "high/low" classification based on KAMs and KIRMs, respectively, were observed between COD angles. Therefore, evaluations at different COD angles are needed to develop an athlete's biomechanical injury risk profile.

Disclosure statement

No potential conflict of interest was reported by the author(s).

References

Andrews, J. R., McLeod, W. D., Ward, T., & Howard, K. (1977). The cutting mechanism. *American Journal of Sports Medicine*, *5*(3), 111–121. https://doi.org/10.1177/036354657700500303

Bates, N. A., Myer, G. D., Shearn, J. T., & Hewett, T. E. (2015). Anterior cruciate ligament biomechanics during robotic and mechanical simulations of physiologic and clinical motion tasks: A systematic review and meta-analysis. *Clinical Biomechanics*, *30*(1), 1–13. https://doi.org/10.1016/j.clinbiomech.2014.12.006

Baudet, A., Morisset, C., d'Athis, P., Maillefert, J.-F., Casillas, J.-M., Ornetti, P., & Laroche, D. (2014). Cross-talk correction method for knee kinematics in gait analysis using principal component analysis (PCA): A new proposal. *PloS One*, *9*(7), e102098. https://doi.org/10.1371/journal.pone.0102098

Besier, T. F., Lloyd, D. G., Cochrane, J. L., & Ackland, T. R. (2001). External loading of the knee joint during running and cutting maneuvers. *Medicine and Science in Sports and Exercise*, *33*(7), 1168–1175. https://doi.org/10.1097/00005768-200107000-00014

Bourgeois, F., McGuigan, M. R., Gill, N. D., & Gamble, G. (2017). Physical characteristics and performance in change of direction tasks: A brief review and training considerations. *The Journal of Australian Strength and Conditioning*, *25*(5), 104–117.https://www.uksca.org.uk/assets/pdfs/UkscaIqPdfs/technical-models-for-change-of-direction-biomechanical-principles-637212405997453524.pdf

Cohen, J. (1988). *Statistical analysis for the behavioral sciences*. Lawrance Erlbaum.

Cortes, N., & Onate, J. (2013). Clinical assessment of drop-jump landing for determination of risk for knee injury. *International Journal of Athletic Therapy and Training*, *18*(3), 10–13. https://doi.org/10.1123/ijatt.18.3.10

Cortes, N., Onate, J., & Van Lunen, B. (2011). Pivot task increases knee frontal plane loading compared with sidestep and drop-jump. *Journal of Sports Sciences*, *29*(1), 83–92. https://doi.org/10.1080/02640414.2010.523087

Cumps, E., Verhagen, E., Annemans, L., & Meeusen, R. (2008). Injury rate and socioeconomic costs resulting from sports injuries in Flanders: Data derived from sports insurance statistics 2003. *British Journal of Sports Medicine*, *42*(9), 767–772. https://doi.org/10.1136/bjsm.2007.037937

Dai, B., William, E. G., Michael, T. G., Darin, A. P., Robin, M. Q., & Bing, Y. (2014). The effects of 2 landing techniques on knee kinematics, kinetics, and performance during stop-jump and side-cutting tasks. *The American Journal of Sports Medicine*, *43*(2), 466–474. https://doi.org/10.1177/0363546514555322

Daniels, K. A., Drake, E., King, E., & Strike, S. (2021). Whole-body change-of-direction task execution asymmetries after anterior cruciate ligament reconstruction. *Journal of Applied Biomechanics*, *37(3)*, 176–181.https://doi.org/10.1123/jab.2020-0110

Dempsey, A. R., Lloyd, D. G., Elliott, B. C., Steele, J. R., & Munro, B. J. (2009). Changing sidestep cutting technique reduces knee valgus loading. *The American Journal of Sports Medicine*, *37*(11), 2194–2200. https://doi.org/10.1177/0363546509334373

Dos' Santos, T., Thomas, C., & Jones, P. A. (2021). How early should you brake during a 180° turn? A kinetic comparison of the antepenultimate, penultimate, and final foot contacts during a 505 change of direction speed test. *Journal of Sports Sciences*, 39*(4)*. doi: 10.1080/02640414.2020.1823130

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The effect of angle and velocity on change of direction biomechanics: An angle-velocity trade-off. *Sports Medicine*, *48*(10), 2235–2253. https://doi.org/10.1007/s40279-018-0968-3

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2019). The role of the penultimate foot contact during change of direction: implications on performance and risk of injury. *Strength and Conditioning Journal*, *41*(1), 87–104. https://doi.org/10.1519/SSC.0000000000000395

Dos'Santos, T., Thomas, C., McBurnie, A., Comfort, P., & Jones, P. A. (2021). Biomechanical determinants of performance and injury risk during cutting: A performance-injury conflict? *Sports Medicine*, Online Ahead of Print. https://doi.org/10.1007/s40279-020-01368-8

Havens, K. L., & Sigward, S. M. (2014). Whole body mechanics differ among running and cutting maneuvers in skilled athletes. *Gait & Posture*, *42*(3), 240–245. https://doi.org/10.1016/j.gaitpost.2014.07.022

Havens, K. L., & Sigward, S. M. (2015a). Cutting mechanics: Relation to performance and anterior cruciate ligament injury risk. *Medicine and Science in Sports and Exercise*, *47*(4), 818–824. https://doi.org/10.1249/MSS.0000000000000470

Havens, K. L., & Sigward, S. M. (2015b). Joint and segmental mechanics differ between cutting maneuvers in skilled athletes. *Gait & Posture*, *41*(1), 33–38. https://doi.org/10.1016/j.gaitpost.2014.08.005

Herrington, L. C., Munro, A. G., & Jones, P. A. (2018). Assessment of factors associated with injury risk. In P. Comfort, J. J. McMahon, & P. A. Jones (Eds.), *Performance Assessment in Strength and Conditioning* (pp. 53–95). Routledge.

Hewett, T. (2017). Preventive biomechanics: A paradigm shift with a translational approach to biomechanics. *The American Journal of Sports Medicine*, *45*(11), 2654–2664. https://doi.org/10.1177/0363546516686080

Hopkins, W. (2004). *How to interpret changes in an athletic performance test*. *Sport science*. A new view of statistics: http://www.sportsci.org/jour/04/wghtests.htm

Hopkins, W. G. (2002). *A scale of magnitudes for effect statistics*. A new view of statistics. http://sportsci.org/resource/stats/effectmag.html

Jones, P. A., Herrington, L., & Graham-Smith, P. (2015). Technique determinants of knee joint loads during cutting in female soccer players. *Human Movement Science*, *42*(1), 203–211. https://doi.org/10.1016/j.humov.2015.05.004

Jones, P. A., Herrington, L., & Graham-Smith, P. (2016b). Technique determinants of knee abduction moments during pivoting in female soccer players. *Clinical Biomechanics*, *31*(1), 107–112. https://doi.org/10.1016/j.clinbiomech.2015.09.012

Lloyd, D. G., & Buchanan, T. S. (2001). Strategies of muscular support of varus and valgus isometric loads at the human knee. *Journal of Biomechanics*, *34*(10), 1257–1267. https://doi.org/10.1016/S0021-9290(01)00095-1

Lohmander, L. S., Englund, P. M., Dahl, L. L., & Roos, E. M. (2007). The long-term consequence of anterior cruciate ligament and meniscus injuries. *American Journal of Sports Medicine*, *35*(10), 1756–1769. https://doi.org/10.1177/0363546507307396

Maniar, N., Schache, A. G., Sritharan, P., & Opar, D. A. (2018). Non-knee-spanning muscles contribute to tibiofemoral shear as well as valgus and rotational joint reaction moments during unanticipated sidestep cutting. *Scientific Reports*, *8*(1), 2501. https://doi.org/10.1038/s41598-017-19098-9

Markolf, K. L., Burchfield, D. M., Shapiro, M. M., Shepard, M. F., Finerman, G. A. M., & Slauterbeck, J. L. (1995). Combined knee loading states that generate high anterior cruciate ligament forces. *Journal of Orthopaedic Research*, *13*(6), 930–935. https://doi.org/10.1002/jor.1100130618

Marshall, B. M., Franklyn-Miller, A. D., King, E. A., Moran, K. A., Strike, S., & Falvey, A. (2014). Biomechanical factors associated with time to complete a change of direction cutting maneuver. *Journal of Strength and Conditioning Research*, *28*(10), 2845–2851. https://doi.org/10.1519/JSC.0000000000000463

McBurnie, A., Dos' Santos, T., & Jones, P. A. (2019). Biomechanical associates of performance and knee joint loads during an 70-90° cutting maneuver in sub-elite soccer players. *Journal of Strength and Conditioning Research*, *Publish Ahead of Print*. Published Ahead of print. https://doi.org/10.1519/JSC.0000000000003252

Montgomery, C., Blackburn, J., Withers, D., Tierney, G., Moran, C., & Simms, C. (2018). Mechanisms of ACL injury in professional rugby union: A systematic video analysis of 36 cases. *British Journal of Sports Medicine*, *52*(15), 944–1001. https://doi.org/10.1136/bjsports-2016-096425

Munro, A. G., Herrington, L., & Comfort, P. (2017). The relationship between 2-dimensional knee-valgus angles during single-leg squat, single-leg-land, and drop-jump screening tests. *Journal of Sports Rehabilitation*, *26* (1), 72–77. https://doi.org/10.1123/jsr.2015-0102

Nimphius, S. (2017). Training change of direction and agility. In A. Turner & P. Comfort (Eds.), *Advanced strength and conditioning*. (pp. 291–308). Routledge.

Onate, J., Cortes, N., Welch, C., & Van Lunen, B. (2010). Expert versus novice interrater reliability and criterion validity of the landing error scoring system. *Journal of Sport Rehabilitation*, *19*(1), 41–56. https://doi.org/10.1123/jsr.19.1.41

Roewer, B. D., Ford, K. R., Myer, G. D., & Hewett, T. E. (2014). The 'impact' of force filtering cut-off frequency on the peak knee abduction moment during landing: Artefact or 'artifiction'? *British Journal of Sports Medicine*, *48*(6), 464–468. https://doi.org/10.1136/bjsports-2012-091398

Sasaki, S., Nagano, Y., Kaneko, S., Sakurai, T., & Fukubayashi, T. (2011). The relationship between performance and trunk movement during change of direction. *Journal of Sports Science and Medicine*, *10*(1), 112–118. https://www.jssm.org/hfabst.php?id=jssm-10-112.xml

Shin, C. S., Chaudhari, A. M., & Andriacchi, T. P. (2011). Valgus plus internal rotation moments increase anterior cruciate ligament strain more than either alone. *Medicine & Science in Sports & Exercise*, *43*(8), 1484–1491. https://doi.org/10.1249/MSS.0b013e31820f8395

Sigward, S. M., Cesar, G. M., & Havens, K. L. (2015). Predictors of frontal plane knee moments during side-step cutting to 45 and 110 degrees in men and women: Implications for anterior cruciate ligament injury. *Clinical Journal of Sport Medicine*, *25*(6), 529–534. https://doi.org/10.1097/JSM.0000000000000155

Sweeting, A. J., Aughey, R. J., Cormack, S. J., & Morgan, S. (2017). Discovering frequently recurring movement sequences in team-sport athlete spatiotemporal data. *Journal of Sports Sciences*, *35*(24), 2439–2445. https://doi.org/10.1080/02640414.2016.1273536

Vanrenterghem, J., Gormley, D., Robinson, M., & Lees, A. (2010). Solutions for representing the whole-body centre of mass in side cutting manoeuvres based on data that is typically available for lower limb kinematics. *Gait & Posture*, *31*(4), 517–521. https://doi.org/10.1016/j.gaitpost.2010.02.014

Vanrenterghem, J., Venables, E., Pataky, T., & Robinson, M. A. (2012). The effect of running speed on knee mechanical loading in females during side cutting. *Journal of Biomechanics*, *45*(14), 2444–2449. https://doi.org/10.1016/j.jbiomech.2012.06.029

Vincent, W. J., & Weir, J. P. (2012). *Statistics in kinesiology*. Human Kinetics.

Walden, M., Krosshaug, T., Bjorneboe, J., Andersen, T. E., Faul, O., & Hagglund, M. (2015). Three distinct mechanisms predominate in non-contact anterior cruciate ligament injuries in male professional football players: A systematic video analysis of 39 cases. *British Journal of Sports Medicine*, *49*(22), 1452–1460. https://doi.org/10.1136/bjsports-2014-094573

Weinhandl, J. T., Earl-Boehm, J. E., Ebersole, K. T., Huddleston, W. E., Armstrong, B. S., & O'connor, K. M. (2014). Reduced hamstring strength increases anterior cruciate ligament loading during anticipated sidestep cutting. *Clinical Biomechanics*, *29*(7), 752–759. https://doi.org/10.1016/j.clinbiomech.2014.05.013

Weir, G., Alderson, J., Smailes, N., Elliott, B., Donnelly, C., & Reliable Video-based, A. (2019). ACL injury screening tool for female team sport athletes. *International Journal of Sports Medicine*, *40*(3), 191–199. https://doi.org/10.1055/a-0756-9659

Welch, N., Richter, C., Franklyn-Miller, A., & Moran, K. (2021). Principal component analysis of the associations between kinetic variables in cutting and jumping, and cutting performance outcome. *Journal of Strength and Conditioning Research*,*35*(7), 1846–1855. https://doi.org/10.1519/JSC.0000000000003028

Winter, D. A. (1990). *Biomechanics and motor control of human motion*. Wiley-Interscience.

Winter, D. A. (2009). *Biomechanics and motor control of human movement*. John Wiley & Sons.

Wyatt, H., Weir, G., van Emmerik, R., Jewell, C., & Hamill, J. (2019). Whole-body control of anticipated and unanticipated sidestep manoeuvres in female and male team sport athletes. *Journal of Sports Sciences*, *37*(19), 2269-2269. https://doi.org/10.1080/02640414.2019.1627982

Yeadon, M. R., Kato, T., & Kerwin, D. G. (1999). Measuring running speed using photocells. *Journal of Sports Sciences*, *17*(3), 249–257. https://doi.org/10.1080/026404199366154